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Modeling and solution of the joint quay crane and truck scheduling problem

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ABSTRACT

This paper addresses the joint quay crane and truck scheduling problem at a container terminal, considering the coordination of the two types of equipment to reduce their idle time between performing two successive tasks. For the unidirectional flow problem with only inbound containers, in which trucks go back to quayside without carrying outbound containers, a mixed-integer linear programming model is formulated to minimize the makespan. Several valid inequalities and a property of the optimal solutions for the problem are derived, and two lower bounds are obtained. An improved Particle Swarm Optimization (PSO) algorithm is then developed to solve this problem, in which a new velocity updating strategy is incorporated to improve the solution quality. For small sized problems, we have compared the solutions of the proposed PSO with the optimal solutions obtained by solving the model using the CPLEX software. The solutions of the proposed PSO for large sized problems are compared to the two lower bounds because CPLEX could not solve the problem optimally in reasonable time. For the more general situation considering both inbound and outbound containers, trucks may go back to quayside with outbound containers. The model is extended to handle this problem with bidirectional flow. Experiment shows that the improved PSO proposed in this paper is efficient to solve the joint quay crane and truck scheduling problem.

1. Introduction

Container terminals are crucial interfaces between land and sea transportation modes. Container ships carry inbound containers to a terminal and carry outbound containers away. At container terminals, containers are transferred from one mode to another (Vis & De Koster, 2003). Inbound containers are unloaded from container ships by quay cranes and then transported by internal trucks to storage yard where they are stacked by yard cranes to their allocated positions waiting for the consignees to pick up. Outbound containers are handled in the opposite direction. Shippers send the containers into the terminal and yard cranes store them in their allocated positions. Later they are retrieved by yard cranes and transported by trucks to quayside where they are loaded onto ships by quay cranes. Fig. 1 illustrates the handling processes for inbound and outbound containers.

As described above, the whole terminal operation is very complex and involves different types of equipments. The operations of the equipments need to be planned appropriately in order to ensure an efficient operation, especially for busy terminals with increasing throughputs.

Operations planning and scheduling at container terminals include berth allocation to incoming ships, quay crane scheduling, ground transport equipment scheduling, yard crane scheduling, storage space allocation, and so on. From the above brief description of terminal operations, we can see that quay cranes are the equipment directly unloading containers from and loading containers to ships. Trucks provide ground transportation of containers between the quay cranes and the storage yard. Effective quay crane scheduling and truck scheduling are both important in terminal management. The operations of quay cranes and trucks are closely linked and need good coordination to avoid efficiency loss due to waiting for each other. Therefore in this paper we study the problem of jointly scheduling quay cranes and trucks.

The paper is organized as follows. In the next section, we first briefly review related research in the existing literature. Then a detailed problem description is given in Section 3. A mixed-integer linear programming model is formulated in Section 4 for the problem with unidirectional flow. Section 5 provides one optimal property, four valid inequalities and two lower bounds for the unidirectional flow problem. A Particle Swarm Optimization (PSO) algorithm is proposed in Section 6 to solve the unidirectional flow problem. Section 7 considers the more general situation with ships

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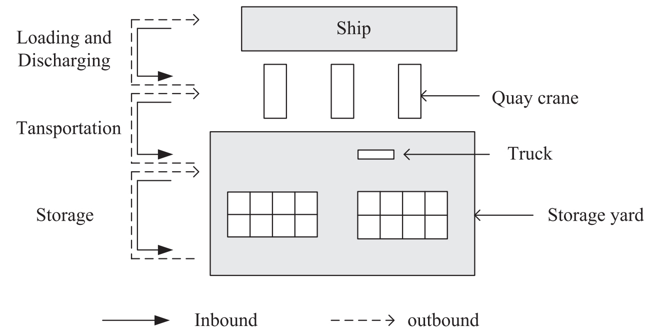

Fig. 1. The handling processes of inbound and outbound containers.

involving both unloading and loading of containers. The model and the PSO algorithm are extended to solve this general problem with bidirectional flow. The lower bounds are also modified to suit the general situation. Experiment results are reported in Section 8 showing that the proposed PSO algorithm is effective and efficient in solving the joint quay crane and truck scheduling problem with unidirectional or bidirectional flow. Section 9 provides conclusions.

2. Literature review

There has been little research on truck scheduling at container terminals. Nishimura, Imai, and Papadimitriou (2005) addressed a trailer routing problem at a container terminal. They formulated both the single-trailer and multi-trailer problems for pickup and delivery of containers in the terminal, and then employed genetic algorithm to solve them. Most previous work on this topic considered problems of scheduling other types of ground transport equipment, such as transfer cranes, straddle carriers, and automated guided vehicles (AGV). For example, Kim and Kim (1997) investigated the routing problem for a single transfer crane and focused on outbound containers to be loaded onto a ship. A straddle carrier routing problem was studied by Kim and Kim (1999), and a beam search algorithm was used for solutions. Vis, De Koster, Roodbergen, and Peeters (2001) determined the minimum number of AGVs at a semi-automated container terminal by a minimum flow algorithm. However, none of the previous ground transport equipment scheduling research considered the link with the quay crane scheduling.

Due to the practical importance of crane scheduling problem, it has received much research attention. Zhang, Wan, Liu, and Linn (2002) studied the dynamic Rubber Tired Gantry Cranes (RTGCs) deployment problem, and a mixed integer programming model has been formulated. In their paper, the objective is to minimize the total workload overflow. The multiple yard cranes scheduling problem with inter-crane interference was examined by Ng (2005), and a dynamic programming-based heuristic was proposed to solve the problem. Research on the quay crane (QC) scheduling problem started twenty years ago (Daganzo, 1989), and the problem received more attention recently. Lim, Rodrigues, Xiao, and Zhu (2004) discussed the quay crane scheduling problem with three particularly common constraints, which were the noncrossing constraint, the neighborhood constraint and the job-separation constraint, and three algorithms were proposed for obtaining solutions. In their study, a job was defined as a collection of cargo from a given area on a ship. Kim and Park (2004) studied the quay crane scheduling problem, in which a cluster of containers to load or unload was called as a task. A branch and bound (B & B) method and a greedy randomized adaptive search procedure (GRASP) were used to obtain solutions. Liu, Wan, and Wang (2006) modeled the quay crane assignment and scheduling problem considering noncrossing requirement and safety distance. The problem was then decomposed to two levels and solved efficiently using smaller models. The sequence for quay cranes to handle holds in one container vessel were decided by Lee, Wang, and Miao (2008), and a genetic algorithm was presented for solving the problem.

There have been also some papers discussing the integration of different decision problems in container terminals. For example, Bish, Leong, Li, Ng, and Simchi-Levi (2001) studied a problem of allocating storage locations for unloading containers as well as dispatching trucks to transport the containers. A heuristic algorithm was proposed to get solutions. A multiple-crane-constrained scheduling problem was also considered by Bish (2003), in which the unloading and loading containers were both contained. A formulation was presented by Imai, Chen, Nishimura, and Papadimitriou (2008) for the simultaneous berth and quay crane allocation problem, and a heuristic was proposed employing genetic algorithm to obtain near solutions. The problem of scheduling both trucks and quay cranes has rarely been studied. Li and Vairaktarakis (2004) proposed an optimal algorithm and some heuristic algorithms to solve the loading and unloading problem with one quay crane and several vehicles. Chen, Bostel, Dejax, Cai, and Xi (2007) considered the integrated scheduling problem of container handling systems including quay cranes, yard cranes and yard vehicles. They viewed the problem as a Hybrid Flow Shop Scheduling problem with precedence and blocking constraints (HFSS-B). Instead of detailed allocation and scheduling of quay cranes to perform the loading/unloading tasks, they assumed that each quay crane covers a given range of bays and that the ranges for different quay cranes are not overlapping to avoid potential collision. Though such a restriction simplifies the problem, it may make the optimal solution infeasible. In this paper we address the joint quay crane and truck scheduling problem and consider conflicts between quay cranes explicitly. We decide not only the assignment of containers to the quay cranes and trucks, but also the sequence of tasks to be performed by each quay crane and each truck.

3. The joint quay crane and truck scheduling problem

When container ships berth at the terminal, the loading and unloading operations are carried out by quay cranes. The quay crane scheduling problem needs to decide the assignment of quay cranes to perform the tasks of handling individual containers and to determine the handling sequence of the containers assigned to each quay crane. The containers unloaded from the ships are to be transported by trucks to the yard for storage; while the containers to be loaded onto the ships need to be transported by trucks from the yard to the quay cranes for loading. The truck scheduling problem assigns the transport tasks to the trucks and decides the handling sequence of containers assigned to each truck. In this paper, we consider the integrated quay crane and truck scheduling problem and make all the above decisions jointly.

In the traditional terminal operation, quay cranes are often scheduled first to process coming ships, and then trucks are assigned to serve specific quay cranes. In this method, each working quay crane is teamed up with a fixed set of trucks. The quay crane and the trucks may often need to wait for each other. Take the unloading process as an example. If a container is unloaded by a quay crane, but none of the trucks has arrived, the quay crane has to hold the container and wait for a truck. On the other hand, if the quay crane has not completed the unloading of a container when a truck comes, the truck has to wait. Such waiting causes productivity loss and shows a need for better coordination between the operations of quay cranes and trucks. As shown in Fig. 2, there are two ships berthed at the terminal. Quay crane 1 and Quay crane 2 are allocated to Ship 1 and Ship 2, respectively.